AD-A090 841 STANFORD UNIV CA DEPT OF MECHANICAL ENGINEERING F/G 20/11
THE ANALYSIS OF METAL-FORMING PROCESSES.(U)
OCT 80 E H LEE, R L MALLETT DAAG29-77-G-0126
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LEVEL II

FINAL REPORT, 25 Apr 77 - 24 Apr 80

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October ~~11, 1980~~

AD A090841

U. S. Army Research Office

Grant DAAG 29-77-G-0126

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THE ANALYSIS OF METAL-FORMING PROCESSES

E. H. Lee and R. L. Mallett

1. Evaluation of Stress and Deformation in Metal-Forming Processes

A complete stress and deformation analysis of a metal-forming process is necessary in order to assess the onset of metal-forming defects such as the initiation of internal or surface cracks, the generation of high residual stresses or the occurrence of local flow abnormalities. In order to evaluate stresses throughout the material it is necessary to carry out an elastic-plastic analysis. Although in metal forming processes elastic strains are usually much smaller than plastic strains, rigid-plastic theory is not appropriate since it cannot predict stresses in the rigid regions. In the actual material these correspond to regions of purely elastic deformation and to regions of contained plastic flow where the total strains are constrained to be of elastic order.

The required finite-deformation elastic-plastic analysis has only recently become feasible due to developments in continuum mechanics for large strain, related computational techniques and computer capacity. A finite-element computer program valid for elastic-plastic analysis at finite strain was developed and was first applied to a problem involving plane strain extrusion through frictionless curved dies. In order to extend this new capability to encompass additional features encountered in practical metal-forming processes, a method of handling friction at metal-tool interfaces was developed. The required non-self-adjoint mathematical description led to a finite-element formulation involving non-symmetric incremental stiffness equations and thus

to substantial modification to the computer program. The results obtained for plane strain and axisymmetric chamber extrusion through curved dies conclusively demonstrated, as argued in the project report [1]*, the feasibility of the required large-strain elastic-plastic analysis and constituted a major step toward the goal of rational assessment of practical metal forming processes.

Numerical accuracy and computational efficiency were emphasized throughout the development of the computer program. In order to efficiently handle materials exhibiting the common saturation of hardening at large strains, considerable revision of the computational procedures was necessary because the flattening of the stress-strain curve generates numerical instability associated with the incompressible nature of plastic flow. Computer program modifications include the introduction of a partial stiffness technique to permit midstep yielding, of a predictor-corrector procedure to establish midstep stresses and yield surface normals, of an exact procedure for tracking the strain hardening curve, and of a constant dilatation isoparametric quadrilateral finite-element, as well as several higher order elements, to improve accuracy in the computed stress distributions. The net result was a marked improvement in accuracy for a given spacial mesh with no appreciable increase in computation time.

As part of an international effort to compare and verify existing elastic-plastic computer codes, the upsetting of a cylindrical billet between rigid parallel platens was analyzed and presented in project report [2]. We have assumed responsbility for planning and coordinating the next phase of the effort. We have compared finite-element and slip-line field theory solutions for a related problem, plane-strain compression of a rectangular block, in

*Numbers in square brackets refer to the bibliography at the end of the report.

which large strains at the block's edges produce folding of the free surfaces against the advancing platens. This phenomenon generates additional computational difficulties. In order to analyze such problems satisfactorily using finite elements, the boundary conditions had to be modified to permit boundary shear slip in the case of perfectly-plastic material.

2. Incremental Elastic-Plastic Theory at Finite Deformation

The plastic part of an elastic-plastic deformation is that remaining when the stress, and hence the elastic strain, is reduced to zero. Elastic deformation is that produced in this un-stressed, purely-plastically-deformed material by the action of stresses up to yield. The exact mathematical representation of the kinematics of such elastic-plastic deformation at finite strain and rotation expresses the total deformation-gradient matrix as the plastic deformation-gradient matrix pre-multiplied by the elastic deformation-gradient matrix [3]. The fact that this operation is not commutative immediately throws doubt on the almost universal assumption in elastic-plastic theory that the total strain-rate is equal to the sum of elastic and plastic strain-rates, for this relation is commutative. An exact analysis based on the nonlinear kinematics, [4], was developed which shows that the theory in current use is in error to the extent of not being objective, i.e. deductions from it may depend on the particular axes chosen to express the deformation.

In order to generate an analytically rigorous theory, the nonlinear, finite-deformation, isotropic, objective, elastic law is used relating the stress to the elastic deformation gradient. In the development of the incremental, or rate type, elastic-plastic relation, the elastic law for stress is

differentiated, yielding rate equations which are therefore also objective. This follows directly from the mathematical manipulation thus avoiding the need to select a particular stress-rate definition [4]. The elastic rate equation and the classical plastic rate relation are substituted into the nonlinear, finite-deformation kinematical theory to generate an elastic-plastic constitutive relation involving rate of stress, rate of total strain, the stress and the work-hardening based on deformation history. This constitutive relation exhibits the symmetry properties to give a rate-potential function [5] and hence a convenient variational principle for finite deformation analysis using the finite-element method [4]. The theory is contrasted with that in common use and anomalies in the latter are discussed. The finite-deformation elastic-plastic theory in current use is generated as an approximation to the rigorous theory, and it is anticipated that this approximation will be adequate for most metal-forming problems. However, it is important from a basic standpoint to know which theory is rigorous and which is approximate, and there may be some problems of plastic instability for which the difference is significant. For situations involving high hydrostatic pressure, such as occur in shock-waves and high-velocity impact, where finite dilatational elastic strains arise, the new theory is needed to provide an adequate analysis [6,7,8].

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A090 841
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) THE ANALYSIS OF METAL-FORMING PROCESSES	5. TYPE OF REPORT & PERIOD COVERED Final 4/25/77 - 4/24/80
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) E. H. Lee and R. L. Mallett	8. CONTRACT OR GRANT NUMBER(s) DAA G 29-77-G-0126
9. PERFORMING ORGANIZATION NAME AND ADDRESS DIVISION OF APPLIED MECHANICS STANFORD UNIVERSITY STANFORD, CALIFORNIA 94305	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709	12. REPORT DATE OCTOBER 13, 1980
	13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Elastic-Plastic Analysis, Stress Analysis, Metal forming, Finite Deformation, Large Deformation, Finite Element Method, Residual Stress Generation.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

see following page

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20. Abstract

A complete stress and deformation analysis of a metal-forming process is necessary in order to assess the onset of metal-forming defects such as the initiation of cracks, the generation of high residual stresses or the occurrence of local flow abnormalities. Rigid-plastic theory can only predict stresses in the regions exhibiting significant current plastic flow so that to evaluate stresses throughout the material it is necessary to carry out an elastic-plastic analysis. A finite-element computer program to evaluate complete stress and deformation distributions has been developed and applied, bringing new insights to the assessment of metal-forming processes.

The plastic part of an elastic-plastic deformation is that remaining when the stress, and hence the elastic strain, is reduced to zero. Elastic deformation is that produced in this purely plastically deformed material by the action of stresses up to yield. The associated exact finite-deformation kinematics shows the almost universal assumption that the total rate of deformation is the sum of elastic and plastic rates to be in error. An incremental elastic-plastic theory is developed using the nonlinear kinematics. The theory is contrasted with that in common use and anomalies in the latter are discussed.

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